

Attorney Docket No. P12048

**REMARKS/ARGUMENTS****1.) Claim Amendments**

Claims 1 through 12 are pending in the application. They have not been amended, but a courtesy copy of the claims is provided above.

**2.) Examiner Objections - Specification**

The specification was objected to because the title of the invention is not descriptive. The Applicant has amended the title of the invention to be more descriptive. The Examiner's approval of the amended title is respectfully requested.

**3.) Claim Rejections – 35 U.S.C. § 103 (a)**

The Examiner rejected claims 1-12 under 35 U.S.C. § 103(a) as being unpatentable over Watterson, et al. (US 6,526,079) in view of Toughlian, et al. (US 6,420,985). The Applicant respectfully traverses this rejection.

For discussion purposes, Claim 1 is reproduced below:

1. An opto-electronic method of converting an analog signal into a digital signal, comprising the steps of:

wavelength modulating a narrowband coherent electromagnetic beam such that the wavelength variation is a monotonic function of the amplitude of said analog signal;

transforming said wavelength modulated beam into a corresponding angularly modulated beam;

diffracting said angularly modulated beam into a bundle of diffracted beams; and

determining said digital signal by repeatedly sampling the spatial power distribution of said diffracted beams.

The Office Action indicates that Watterson discloses an opto-electrical method of converting an analog input signal to a digital signal that comprises the steps of modulating a narrowband electromagnetic beam based on the amplitude of the analog signal, transforming the wavelength modulated beam into an angular modulated beam and diffracting modulated beam into a bundle of diffracted beams. The Applicant respectfully disagrees.

The cited portion of Watterson is reproduced below:

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EUS/J/P/04-8726

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Such a phase plate will produce secondary optical beams at angles which are positive and negative multiples of  $\theta_{\text{diffract}} = \lambda_{\text{laser}} / \lambda_{\text{grating}}$ . The relative magnitude of the diffracted beams is controlled by the magnitude of the maximum phase retardation.

In contrast, the relevant portion of claim 1 comprises two elements: (1) transforming said wavelength modulated beam into a corresponding angularly modulated beam; and (2) diffracting said angularly modulated beam into a bundle of diffracted beams. Assuming *arguendo*, that Watterson teaches an element which corresponds to the transforming element of claim 1, Watterson does not also teach diffracting the angularly modulated beam into a bundle of diffracted beams.

Similarly, Toughlian does not transform a wavelength modulated beam, nor does Toughlian diffract an "angularly modulated beam." At most, Toughlian only splits a wavelength modulated beam into different parts. Thus, neither Watterson nor Toughlian teach all of the elements of claim 1.

As provided in MPEP § 2143, "[t]o establish a prima facie case of obviousness, ... the prior art reference (or references when combined) must teach or suggest all the claim limitations." Furthermore, under MPEP § 2142, "[i]f the examiner does not produce a prima facie case, the applicant is under no obligation to submit evidence of nonobviousness." It is submitted that Watterson and Toughlian do not teach all the elements of claim 1. Consequently, the office action does not factually support a *prima facie* case of obviousness for claim 1 based on a combination of Watterson and Toughlian.

The Examiner also notes that the combination of Watterson and Toughlian do not explicitly teach the sampling of the power distribution repeatedly. However, the Examiner argues that "it is well known in the art of analog to digital converter to timely and repeatedly sample the analog input signals." The Applicant respectfully reminds the Examiner that claim 1 is directed to the *entire* combination of elements and not individual elements of claim 1. Thus, the motivation should be directed to the entire combination and not applied to individual elements.

In any event, the Examiner is either relying on his personal knowledge or by what is "well known in the art" to justify the combination. As the Examiner is aware, in order preserve the Applicant's right to traverse this assertion in later actions, the Applicant is

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forced to traverse this assertion in this Office Action. Thus, the Applicant respectfully traverses the assertion that these limitations are obvious in light of what is "well known in the art" and, as permitted under MPEP § 2144.03, requests that the Examiner cite a reference in support of his position for each rejected claim.

Alternatively, if the Examiner is relying on his personal knowledge as the basis for these assertions, Applicant respectfully objects to the Examiner's use of official notice. Under MPEP § 2144.03, official notice may only be taken of "facts outside of the record which are capable of instant and unquestionable demonstration as being 'well-known' in the art." (Emphasis added). When a rejection is based on facts within the personal knowledge of the Examiner, the facts must be as specific as possible, and the reference must be supported, when called for by the applicant, by an affidavit of the Examiner, which may be subject to explanation by the Applicant. 37 CFR 1.104(d)(2). Pursuant to 37 CFR 1.104(d)(2), the Applicant respectfully requests the Examiner provide such supporting facts and evidence in the form of an affidavit, so that, if necessary, the Applicant may have a chance to explain the reference in later actions.

In any event, neither Watterson nor Toughlian teach all of the elements of claim 1. So, according to the MPEP 2143, an obvious rejection is not proper and should be withdrawn.

Claim 3 is patentable for the same reasons that claim 1 is patentable. Claims 2, 4-12 depend from claims 1 and 3, respectively and recite further limitations in combination with the novel elements of claims 1 and 3. Therefore, the allowance of claims 2 and 4-12 is also respectfully requested.

Watterson and Toughlian Are Not Prior Art:

The present application is a continuation of International Application No. PCT/SE00/01561 filed on August 10, 2000 which claims priority to a Swedish Application filed on August 12, 1999. Thus, the priority date for the present application is August 12, 1999.

Watterson was filed on August 10, 2000 from a provisional patent application filed on August 10, 1999. Watterson's provisional patent application is enclosed as Attachment "A." Toughlian was filed on April 19, 2000 from a provisional patent

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application filed on April 20, 1999. Toughlian's provisional patent application is enclosed as Attachment "B."

Because both Watterson and Toughlian have filing dates that are later than the priority date of the present application, Watterson and Toughlian can only be used as prior art if the cited elements also appear in their respective provisional applications. It is the Applicant's position that certain claim elements are not disclosed nor implied in the provisional applications. Therefore, Watterson and Toughlian cannot be used to defeat patentability of the present application.

For instance, claim 1 states:

1. An opto-electronic method of converting an analog signal into a digital signal, comprising the steps of:  
wavelength modulating a narrowband coherent electromagnetic beam such that the wavelength variation is a monotonic function of the amplitude of said analog signal;  
transforming said wavelength modulated beam into a corresponding angularly modulated beam;  
diffracting said angularly modulated beam into a bundle of diffracted beams; and  
determining said digital signal by repeatedly sampling the spatial power distribution of said diffracted beams.

The Examiner states that the element of "wavelength modulating a narrowband coherent electromagnetic beam such that the wavelength variation is a monotonic function of the amplitude of said analog signal" is taught in Watterson. However, this element is not taught in Watterson's provisional application. Additionally, as discussed above, Watterson's provisional application also does not teach both the elements of "transforming" and "diffracting."

It appears that Toughlian's provisional simply discloses a tunable filter. It does not appear that Toughlian's provisional teaches photo detectors to covert the wave length into binary or Gray coded binary count. Furthermore, Toughlian's provisional patent does not appear to teach the possibility of transforming a wavelength into an array waveguide using a particular filter. Thus, assuming *arguendo*, that Watterson and Toughlian teaches the elements cited by the Examiner, it is clear that these elements are not taught by the corresponding provisional applications. Thus, the relevant priority date for these elements is after the priority date of the present application. Watterson

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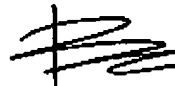
and Toughlian, therefore, cannot be used as prior art. The Applicant, therefore, respectfully requests that these rejections be withdrawn.

### CONCLUSION

In view of the foregoing remarks, the Applicant believes all of the claims currently pending in the Application to be in a condition for allowance. The Applicant, therefore, respectfully requests that the Examiner withdraw all rejections and issue a Notice of Allowance for all pending claims.

The Applicant requests a telephonic interview if the Examiner has any questions or requires any additional information that would further or expedite the prosecution of the Application.

Respectfully submitted,



Bill R. Naifeh  
Registration No. 44,962

Date: 6-14-04

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## ATTACHMENT A

PATENT IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of: Reich Watterson, Parviz Tayebati, Kevin McCallion

For: Single Etalon Optical Wavelength Reference Device

Attorney's Docket No.:-

Date: August 10, 1999

Box Provisional Patent Application  
Assistant Commissioner for Patents  
Washington, DC 20231

Sir:

FILING OF PROVISIONAL PATENT APPLICATION UNDER 37 CFR 1.10

The attached provisional patent application is being filed under the provisions of 37 CFR 1.10.

Applicant's attorney is also submitting the requisite fee and a PROVISIONAL APPLICATION COVER SHEET.

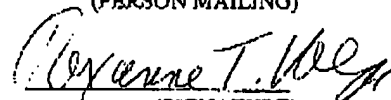
Respectfully submitted,

Parviz Tayebati  
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25 B Street  
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I HEREBY CERTIFY THAT THIS PAPER OR FEE IS BEING DEPOSITED  
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ROXANNE T. VOLPE  
(PERSON MAILING)

  
(SIGNATURE)

A / PROV

## Provisional Application Cover Sheet

This is a request for filing a provisional application under 37 CFR 1.53 (b)(2).

Docket number		Type a plus sign inside this box	
Inventor (s) Applicant (s)			
Last Name	First Name	M/I	Residence Address
Watterson Tayebati McCaflion	Reich Parviz Kevin		18 Battlegreen Road, Lexington, MA 02421 118, Pierce Road, Watertown, MA 02172 127 St. Botolph Street, Apt. 9, Boston, MA 02115
Title of the Invention			
Single Etalon Optical Wavelength Reference Device			
Correspondence Address			
Parviz Tayebati, PhD CoreTek, Inc. 25 B Street Burlington			
State	MA	Zip Code	01803
Country	USA		
Enclosed Application Parts			
<input checked="" type="checkbox"/> Specification	Number of Pages	<input type="checkbox"/> Small Entity Statement	
<input checked="" type="checkbox"/> Drawing(s)	Number of Sheets	Other specify	
Method of Payment (check One)			
<input checked="" type="checkbox"/> A check or money order is enclosed to cover the Provisional Filing fees	Provisional Filing Fee Amount (\$)		\$75
<input type="checkbox"/> The commissioner is hereby authorized to charge filing fees and credit deposit Account Number			

Respectively submitted,

Signature



Date:

8/10/99

Typed Name or Printed Name Parviz Tayebati

Registration No. \_\_\_\_\_

**\*CoreTek, Inc.**  
**Innovative Photonic Devices and Systems**

25 B Street  
Burlington, MA 01803-3406  
Tel: (781) 273-2005  
Fax: (781) 273-2009

**DATE:** 6 August 1999

**SUBJECT:** Provisional Patent Disclosure

**INVENTORS:**

Reich Watterson  
Parviz Tayebati

**I. Title:**

Single Etalon Optical Wavelength Reference Device

**II. Field of the Invention**

Wavelength locking of lasers and optical test instruments.

**III. Background of the Invention**

An optical frequency-locking device requires a subsystem to provide a precise reference frequency. Such references have been designed using molecular absorption lines or air spaced Fabry-Perot etalons.

**IV. Objects of the Invention**

The object of this invention is to provide a temperature stable wavelength reference device in a low cost compact device. Multiple wavelength (or alternatively frequency) references located at previously defined absolute locations are generated. Two signals generated simultaneously by passing collimated light through a single etalon at two distinct angles provides the information needed for absolute frequency determination on an evenly spaced frequency (i.e. ITU) grid.

**V. Summary of the Invention**

1. A single Fabry-Perot etalon provides the information to both locate and identify known frequencies.
2. Illuminating the etalon with collimated light simultaneously at two slightly different directions will generate two optical transmission combs that are slightly offset from each other in frequency.
3. The free spectral ranges of the two combs are chosen not equal to the channel grid spacing. This feature causes the two combs to move in frequency to move relative to each as one moves from ITU channel to ITU channel.
4. The free spectral ranges of the two combs are chosen in combination with the Fabry-Perot bandwidth in such a manner that moving from ITU frequency to frequency the two combs move relative to each other.
5. The ratio of the signals passed through the two frequency combs may be used to determine the absolute frequency. This ratio may be employed for frequency (wavelength) locking purposes.



6. The ratio corresponding to each desired ITU frequency is stored in a lookup table, which the controller uses for channel determination.
7. The controller may use the equal intensity frequency (where the two passbands cross) to narrow the search range in the vicinity of the ITU grid frequencies.
8. The controller then moves the tuning voltage in such a manner as to find either the local maximum or local minimum in detector signal ratio. A lookup table determines whether a maximum or minimum is needed.
9. Locking is achieved by forcing the detector signal ratio to the desired value, thus locking to a desired frequency.

#### VI. Brief Description of the Drawings

1. Figure shows a typical optical layout. Light is input to the device via an optical fiber and collimation device. Light then passes through a beam splitter/deviation device. This device may be an optical phase plate for example or an optical wedge prism. The two slightly divergent beams then pass through the etalon. The different angles of incidence lead to different free spectral range values for the two beams as they pass through the same etalon. Finally, a focussing lens focuses the two beams onto two separate detectors. The controlling electronic circuit to locate and lock to known frequencies then uses the electrical signals produced by the detectors.

#### VII. Detailed Description of the Preferred Embodiments

1. An optical system is sought which will produce a previously known transmission ratio. This ratio changes in a well-defined manner as the source frequency is moved from frequency to frequency lying on the desired grid.
2. The transmission of a Fabry-Perot etalon consists of peaks (frequencies of maximum transmission) spaced with an interval in frequency units corresponding to the etalon free spectral range value (FSR). For example, an etalon designed for the telecommunications band (1520-1560 nm) and a channel interval of 50 GHz would normally have a FSR value of 50 GHz.
3. For the proposed design, we chose two free spectral range (FSR) values. One FSR is slightly larger than the grid spacing; the second is slightly smaller than the grid spacing. These values are chosen such that integer multiples of both lie either above or below the starting frequency for the design band. The two integers are distinct (this fact is crucial). A typical arrangement of suitable transmission functions is shown in Fig. 2. In this case the initial channel is at the low frequency end of the band, starting from the high frequency end is also possible. Note that the FSR value of the etalon, which has a transmission maximum, which is closer to the grid frequency, is larger than the nominal grid spacing. The FSR value of the etalon, which has a transmission maximum, which lies further from the ITU frequency, is actually lower than the ITU grid spacing. Obviously the order number of the second etalon must be larger than the first etalon in this case. The zero frequency offset shown in Figure 1 corresponds to the frequency which we would like to lock to.
4. The order numbers of the two etalons are chosen such that the magnitude of the deviation of each FSR from the desired grid spacing (50 GHz in this example) is essentially equal.

5. As the source frequency is changed from channel to channel the two passbands move relative to each other and relative to the nearest channel frequency. The effect of such shifts results in unique transmission ratios for each channel on the grid.
6. The width of either passband is determined by the finesse (which is a function of the plate reflectivity values).
7. The values of free spectral range, orders and finesse are chosen as a function of the channel to channel change in the transmission ratio and the number of channels to be determined.

#### **VIII. Modifications of the Preferred Embodiments**

1. Beam splitting and deviation may be performed using optical wedges.
2. Beam splitting and deviation may be performed using mirrors.
3. Beam splitting and deviation may be performed using folded optical paths rather than as shown.
4. The two distinct free spectral ranges may be arranged to cross at the desired ITU frequencies rather than offset from the ITU frequency. In this case, the off-grid ratio is used to determine the absolute frequency and the equal power point (ratio= 1) is used for locking.

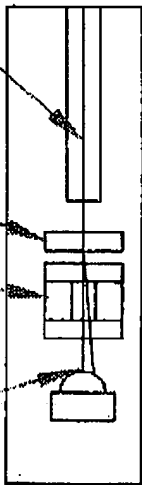
#### **IX. Advantages of the Invention**

1. Compact device to generate both a comb of reference frequencies and to provide an absolute frequency reference.
2. Single etalon, lower cost device.
3. Thermally stable wavelength reference. Temperature control not required.

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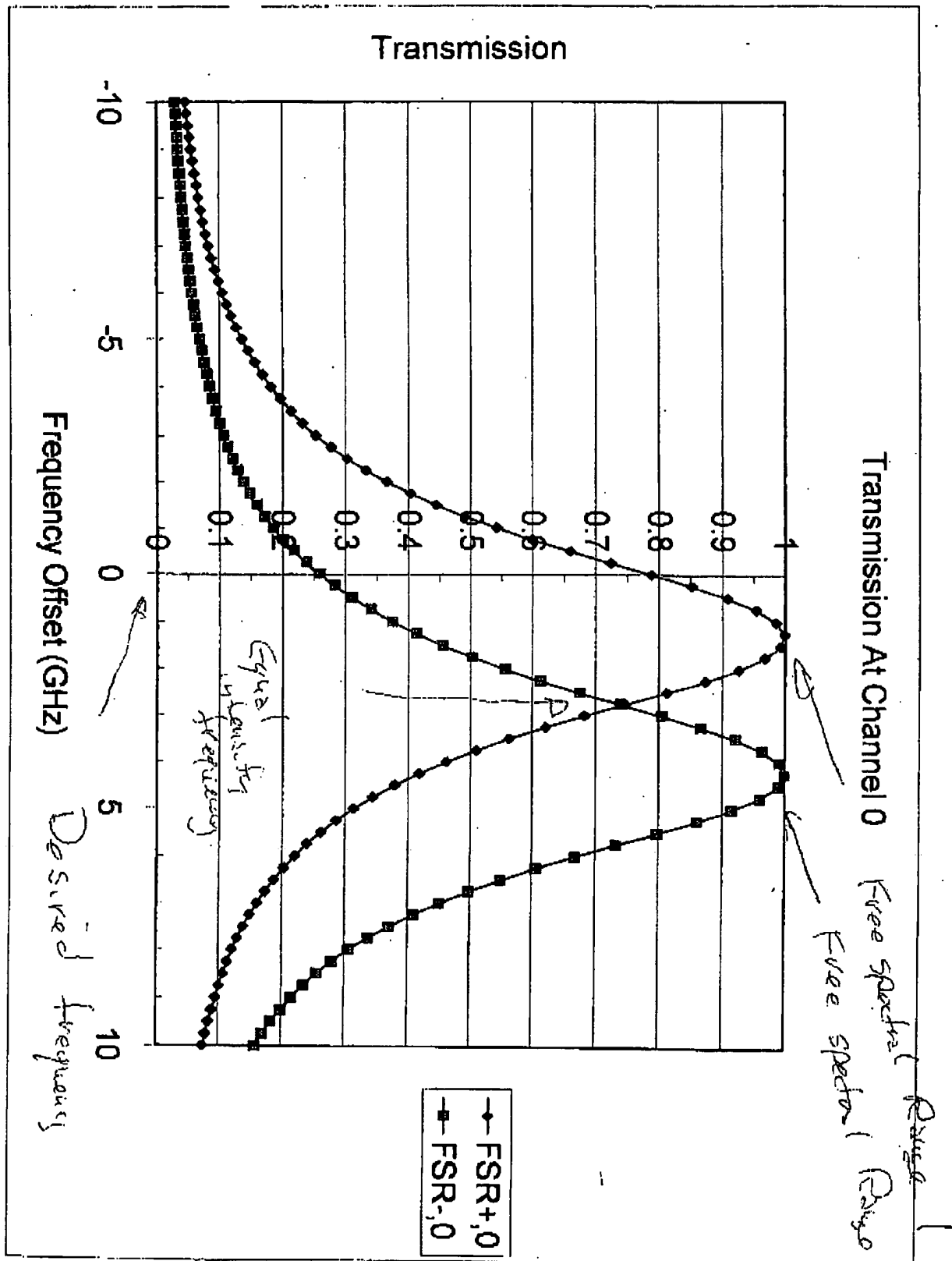
## Single Etalon Wavelength Reference



Optical Input and Collimation Assembly

Beam Splitting and Deviating Assembly

Double Detector/Lens Assembly



## ATTACHMENT B

## PROVISIONAL APPLICATION COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION under 37 CFR 1.53 (b)(2).

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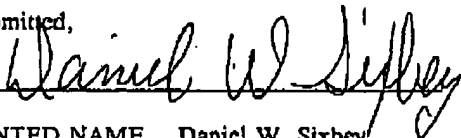
		Docket No. 0883-69	Type a plus sign (+) inside this box →		+
INVENTOR(S)/APPLICANT(S)					
Last Name	First Name	Middle Initial	Residence (City and either State or Foreign Country)		
Toughlian Zmuda	Edward Henry	N.	Melbourne, Florida Shalimar, Florida		
TITLE OF THE INVENTION (280 characters max)					
A HIGH SPEED-HIGH RESOLUTION BROADLY TUNABLE OPTICAL FILTER					
CORRESPONDENCE ADDRESS					
Daniel W. Sixbey SIXBEY, FRIEDMAN, LEEDOM & FERGUSON, P.C. 8180 Greensboro Drive, Suite 800 McLean, Virginia 22102					
STATE	VA	ZIP CODE	22102	COUNTRY	U.S.A.
ENCLOSED APPLICATION PARTS (check all that apply)					
<input checked="" type="checkbox"/> Specification (6 pages)			<input type="checkbox"/> Small Entity Statement		
<input checked="" type="checkbox"/> Drawings (1 sheets)			<input type="checkbox"/> Other (specify)		
METHOD OF PAYMENT (check one)					
X	A check or money order is enclosed to cover the Provisional Filing Fees			Provisional Filing Fee Amount(s)	\$150
X	The Commissioner is hereby authorized to charge filing fees and credit Deposit Account No. 19-2380 (6014-1)				

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☐ No.☐ Yes, the names of the U.S. Government agency and the Government contract number are: \_\_\_\_\_

Respectfully submitted,

SIGNATURE

Date March 29, 1999TYPED or PRINTED NAME Daniel W. SixbeyREGISTRATION NO. 20,932☐ Additional inventors are being named on separately numbered sheets attached hereto.

## PROVISIONAL APPLICATION FILING ONLY

## A High Speed - High Resolution Broadly Tunable Optical Filter

Edward N. Toughlian  
ENSCO, Inc.  
Applied Research and  
Systems Division  
Cocoa Beach, Florida

Henry Zmuda  
University of Florida  
Graduate Engineering and  
Research Center  
Shalimar, Florida

### ABSTRACT

*This disclosure describes how an electrooptic phase modulator operating in conjunction with optical waveguide/fiber Bragg grating reflectors and other commonly available photonic components can be used to perform the process of high speed, high resolution broadband filtering. The tunable filter described here has high tuning speed (sub nanosecond), high resolution (tens of picometers), and broad tuning range (several tens of nanometers) as controllable design parameters. The filter achieves the desired performance using only a few common optical components, and is suitable for fabrication either discretely or as a photonic integrated circuit. It is anticipated that this product will find many uses in the telecommunication, radar, and satellite systems areas as well as offer improved capabilities for high-speed test equipment such as network and spectrum analyzers and real time broadband oscilloscopes. Due to the minimal number of active components and the ease of manufacturability of all components used within this system, it is likely that this approach will yield a system which will become a viable solution for many DOD applications and in the near future, a practical and cost effective solution for commercial business and home use applications as well.*

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### 1. Introduction

The desire to capture the tremendous information carrying capacity of optical fiber has resulted in the identification of Wavelength Division Multiplexing (WDM) as the dominant architecture for future telecommunication systems. An essential attribute of WDM systems is the ability to efficiently encode information onto independent channels separated in wavelength at the sending end and to randomly and rapidly access any channel at the receiving end. A key component for WDM systems is a tunable filter. The desired characteristics of tunable filters include a wide tuning range, a large number of accessible frequency channels, and simple control. In addition, fast channel switching time with a low amplitude control signal is essential in most applications. This control signal can be a binary word in some applications, while in others it may be a microwave signal. The need for tunable filters, or equivalently tunable sources, is not limited to the WDM application. Microwave signal processing (optically controlled phased array antennas for example), high speed test and measurement equipment, radar, and cellular communications all either benefit from or require rapid reconfigurability.

The ability to achieve all the desired characteristics mentioned above has been a major challenge and several significant inroads have been made. The traditional tunable

laser structures using distributed Bragg reflection can, at most, produce optical frequency shifts  $\Delta f$  in direct proportion to the induced refractive index change  $\Delta n$  which tends to be quite small [1]. Semiconductor lasers tuned via carrier injection have tuning speeds of a few nanoseconds, limited by carrier lifetimes [2]. Also, carrier injection tuning tends to be discrete and exhibits highly nonlinear frequency vs. tuning control (current) characteristics. High speed tunability over a wide range can be achieved by tuning over individual Fabry-Perot modes using a Mach-Zehnder filter, but at the expense of reduced resolution [3]. The resolution can be increased, but at the expense of a complex implementation using a cascade of Mach-Zehnder filters with geometric path imbalances [4].

## 2. Technical Description

### *Bragg Reflection Gratings*

A fundamental element for the tunable filter described below is the fiber or waveguide-based Bragg Reflection Grating (BRG). In their basic form, a (uniform) BRG is a waveguide device that will reflect incident energy of a specific wavelength, the Bragg wavelength, while transmitting all others. BRGs are realized by introducing a specified periodic longitudinal perturbation along an otherwise uniform waveguiding structure. The reflection bandwidth and reflectivity are readily controlled design parameters with reflection bandwidths ranging from 0.01 to 100 nanometers. Broad reflection bandwidths are often obtained by using a nonuniform (chirped) spatial perturbation along the guiding axis [5]. Chirped gratings have found widespread application in dispersion compensation for long-haul fiber telecommunications and are a crucial component in the discussion to follow [6]. For a linearly chirped Bragg grating, the effective reflection point along the grating varies linearly with wavelength. For either uniform or chirped gratings, reflectivity at the Bragg wavelength can be as low as 1% or greater than 99.9%, with off-wavelength transmission nearly 100%. Consequently, BRGs are an extremely efficient and versatile optical design element. Their use in various optical systems, especially in the area of WDM telecommunications, has made the fabrication process a mature, well-understood technology.

### *VCTF Theory of Operation*

The underlying structure of the VCTF is the Fabry-Perot (FP) cavity. Let us then begin the explanation of the VCTF operation with a brief review of FP cavities. The basic theory of a FP resonator is well known, and we simply state only those results needed to understand the VCTF operation [7]. The basic FP cavity is a fixed length  $x$  of optical waveguide with refractive index  $n_{eff}$  and terminated at each end with mirrors. In theory these end mirrors are slightly less than 100% reflective to allow a means to insert and extract energy from the cavity. Suppose an optical signal is incident on one of the end mirrors. Since the reflectivity of this mirror is high, a small amount of optical energy enters the cavity and resonates, that is it "bounces back-and-forth" between the mirrors with a small amount of this energy exiting the resonator with each "bounce". If the wavelength of the incident light is such that it adds constructively over the spatial extent

of the cavity, the steady-state output amplitude can equal the input amplitude. This is the cavity resonance condition, and will occur for wavelengths  $\lambda_R$  which correspond to the round-trip distance  $2x$  which produces a phase-shift that is an integer multiple of  $2\pi$  radians, or

$$m\lambda_R = 2n_{eff}x, \quad m = 1, 2, 3, \dots \quad (1)$$

where  $m$  is a fixed integer which accounts for the fact that the cavity can be many wavelengths long.

Suppose we now replace one of the partially reflecting mirrors in the FP resonator with a narrowband BRG which only reflects wavelength  $\lambda_R$ . For a given value of index  $n_{eff}$ , if we wish to establish a resonant condition at wavelength  $\lambda_R$ , then we must physically place the BRG at the value of  $x$  determined by Equation (1). If we were to change the index  $n_{eff}$  leaving everything else the same, Equation (1) would no longer be satisfied. If the half-power bandwidth of this cavity is sufficiently small, a small change in the refractive index can turn the cavity "off" from its  $\lambda_R$  resonance. Unlike the basic FP cavity, no other wavelengths resonate since the BRG acts as a mirror only for  $\lambda_R$ . This idea forms the basis for the VCTF operation.

As an example, consider the simple filter of Figure 2a, which uses four cascaded discrete BRGs to select one of four possible wavelengths  $\lambda_i$ ,  $i = 0, \dots, 3$ . Each BRG in the cascade is placed so that only one wavelength will resonate for a given Electro-Optic (EO) modulator refractive index  $n_i$  as determined by the input voltage  $v_{in}$ . Specifically, the distance  $x_i$  from the partially reflecting mirror to the  $i^{th}$  grating forms a cavity that is designed so that resonance is supported when

$$m_i\lambda_i = 2n_i x_i. \quad (2)$$

As explained above, the other three, non-resonant wavelengths, though reflected by their corresponding BRGs, do not see the necessary conditions required to support their resonance. As previously noted, BRGs can have a narrow reflection bandwidth and high reflectivity. Therefore, cavity theory tells us that only a small change in refractive index of the EO modulator is required to move one wavelength "off-resonance" and its neighboring wavelength "on-resonance". To obtain a broad tuning range with high resolution requires a cascade of a "large number" BRGs. This spatial distribution of BRGs can effectively be accomplished with a single BRG whose wavelength is "chirped" over the desired tuning range (at a chirp-rate that gives the necessary relative wavelength spacing,  $x_{eff}$ ). Thus the cascade of discrete BRGs can be replaced with one "complex" grating structure, in this case a single chirped Bragg grating as shown in Figure 2b.

### VCTF Tuning Speed

The transmission characteristics of the resonant cavity, as described above, tacitly assumes steady-state operating conditions. Earlier we described how a resonant condition



is established in a cavity when the light is added constructively each time it "bounces back-and-forth" inside the cavity. When one realizes that for high reflectivity mirrors it may take many such bounces before the steady-state condition is obtained, it is not hard to see that this transient response can be relatively "slow". Hence, the VCTF requires sufficient time to reach this steady-state operating condition. In order to address the question of tuning speed a detailed transient analysis of the tunable filter must be undertaken. We first do this qualitatively followed by rigorous mathematical reasoning. As we shall see, when the system is first turned-on and an initial steady-state operating condition is reached, energy stored in the cavity at one wavelength may be "rapidly" transferred to another wavelength, specifically as rapidly as the EO modulator's refractive index changes.

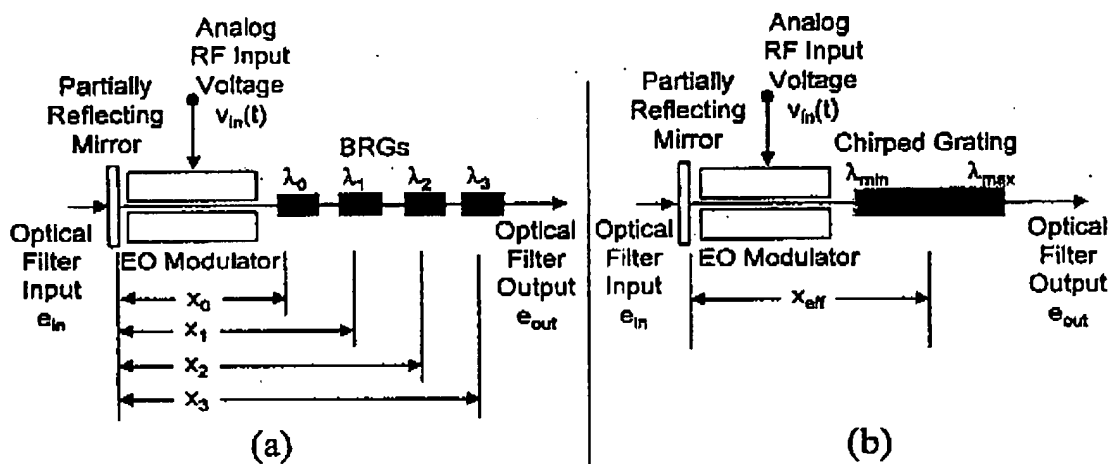


Figure 1: Voltage Controlled Tunable Filter; a) for discrete wavelengths, b) using a single chirped grating.

### VCTF Tuning Speed: Qualitative Discussion

Consider an source with wavelength range occupying a total bandwidth of  $\Delta\lambda$  applied to the filter input. This applied optical input may either be a broadband source that spans this wavelength range  $\Delta\lambda$ , or it may be a set of  $N$  discrete lines. There are two major factors that contribute to the transient response of the VCTF. The first is the transient response of the optical output due to changes in the optical input. The second is the transient response of the optical output due to changes in the applied RF signal voltage  $v_{in}$ . The fact that the refractive index changes with time (as  $v_{in}$  changes with time) means that the system must be modeled a *time-varying* system (linearity is implied). The response of any linear system, time-varying ones included, may be expressed as the superposition of the *zero-state response* plus the *zero-input response*. The zero-state

response is the response of the system due to an applied input when the system is started at rest (zero initial conditions) while the zero-input response represents the output due to the initial conditions acting alone. Note that it is exactly the zero-state response described earlier by the steady-state resonance condition, since we assumed that no energy initially resided in the cavity. The situation is quite different for the zero input response. When the refractive index of the cavity changes, energy *already present (stored)* in the cavity serves as an initial condition that drives the cavity at the resonant frequency determined by this *new* value of refractive index. This response happens as fast as the index changes, and the speed of the filter is determined by the "slowest" element in the system. Of course the response due to initial conditions decays exponentially with time, but this decay rate will be "slow" since it is determined by the zero-state response. Furthermore, recall that the broadband input signal is applied to the system for all time, so energy is continually being "pumped" back into the cavity hence mitigating the decay.

### VCTF Tuning Speed: Mathematical Foundation

The preceding discussion fully described the fundamental mechanisms that governed the tuning speed of the VCTF, but in a qualitative fashion. The formal mathematical justification of those concepts will now be discussed.

As previously noted, classical state-space techniques can be used represent the state (response)  $x(t)$  of a linear, time-varying system at any time  $t$  by the superposition of the *zero-input response* and the *zero-state response*, or

$$x(t) = \varphi(t, t_0)x(t_0) + \int_{t_0}^t \varphi(t, \tau)e_{in}(\tau)d\tau \quad (3)$$

where  $\varphi(t, t_0)$  is the *state transition function* or the natural response of the system. The first term on the right-hand-side of Equation (3) is the *zero-input response* and represents the response of the system due to the initial conditions (initial state  $x(t_0)$ ) alone. The second term on the right-hand side is the *zero-state response* and represents the response of the system to an external optical input  $e_{in}(t)$  with the system initially at rest.

To understand the transient behavior of the tunable filter, consider the specific case where the cavity index is  $n_0$  for  $t < t_0$  and changes instantly to  $n_1$  at  $t = t_0$ . Let us *design* the cavity so that it resonates at (radian) frequency  $\omega_0$  for index  $n_0$  and at  $\omega_1$  for index  $n_1$ , and let us drive this cavity with

$$e_{in}(t) = e^{j\omega_0 t} + e^{j\omega_1 t} \quad (4)$$

Note that causality requires the response for  $t < t_0$  cannot be affected by what happens at  $t = t_0$ . For example, the cavity cannot know that the index will change, so the response for  $t < t_0$  must be identical to the response of a time invariant cavity with index  $n_0$  that never changes. This well known result from system theory can be expressed

$$e_{out}(t) = H(\omega_0)e^{j\omega_0 t} + H(\omega_1)e^{j\omega_1 t}, \quad t < t_0, \quad t_0 \gg 0, \quad (5)$$

where  $H(\omega)$  is the cavity's steady-state transfer function. Note we have assumed that the time  $t_0$  is sufficiently large so that the cavity has reached its steady-state response when the input is changed. This last assumption was made simply to facilitate the writing of the cavity response  $e_{out}(t)$  for  $t < t_0$ . For  $t < t_0$ , frequency  $\omega_0$  resonates while  $\omega_1$  does not. Thus, assuming a sufficiently narrow optical bandwidth  $H(\omega_0) \gg H(\omega_1)$  we have

$$e_{out}(t) \approx H(\omega_0)e^{j\omega_0 t}, \quad t < t_0 \quad (6)$$

Now for  $t > t_0$  (note the strict inequality) we may write the response  $\tilde{e}_{out}(t)$  as

$$\tilde{e}_{out}(t) = e_{out}(t_0)\varphi(t-t_0)|_{n=n_1} + \int_{t_0}^t \varphi(t-\tau)|_{n=n_1} e_{in}(\tau) d\tau \quad t > t_0 \quad (7)$$

or

$$\tilde{e}_{out}(t) = H(\omega_0)e^{j\omega_0 t_0} \varphi(t-t_0)|_{n=n_1} + \int_{t_0}^t \varphi(t-\tau)|_{n=n_1} e_{in}(\tau) d\tau \quad t > t_0 \quad (8)$$

Since the system is time-invariant for  $t > t_0$ , we may replace  $\varphi(t, \zeta)$  with  $\varphi(t-\zeta)|_{n=n_1, t > t_0}$  as was done in Equations (7) and (8). Equation (8) shows that the response for  $t > t_0$  consists of two terms. The second term on the right-hand side is the convolution of the state transition function with the input signal. This is the "bouncing back-and-forth" term of our earlier qualitative description. This term builds up "slowly" as previously discussed and serves to "pump" energy back into the cavity. The first term on the right-hand side however varies in time as  $\varphi(t-t_0)|_{n=n_1}$ , which is the state transition function of a cavity with resonant frequency  $\omega_1$  but with amplitude  $\text{Re}\{H(j\omega_0)e^{j\omega_0 t_0}\}$  which is proportional to the "old" resonant condition. The first term on the right of Equation (8), i.e., the component of the optical output that changes rapidly is then

$$\text{Re}\{\varphi(t-t_0)|_{n=n_1} H(\omega_0)e^{j\omega_0 t_0}\} = \varphi(t-t_0)|_{n=n_1} |H(\omega_0)| \cos(\omega_0 t_0 + \angle H(\omega_0)) \quad (9)$$

Hence the energy stored by the cavity is transferred to the new resonant frequency at  $\omega_1$  as quickly as the index changes as claimed. Equation (9) suggests that if the index could change instantaneously, then the possibility exists for sampling at time  $t_0$  such that the cosine term is zero. Even the fastest phase modulator can operate at speeds no greater than 100 GHz, which corresponds to a rise time three orders of magnitude slower than an

optical period in the 1.55 micron neighborhood. Therefore, the actual output will be the convolution of the EO modulator response with the optical signal ensuring that sampling at a "zero" is not possible.

One question that may remain in the reader's mind is "what is the exact form for the state transition function  $\varphi(t - t_0)$ ?" Answering this question requires a detailed solution of the coupled partial differential equations describing the cavity. This solution become rather involved, but a reduced functional form of the state transition function can be stated as

$$\varphi(t - t_0) = \text{Constant} \cdot e^{(i\omega_1 \pm \beta_1 x)} u(t - t_0) \quad (10)$$

where  $u(x)$  is the unit-step function,  $\beta_1 = \omega_1/c$  is the phase constant for the waveguide and  $c$  is the speed of light in air. The presence of the unit-step in Equation (10) indicates that the total response will contain a component that changes instantly. Though not explicitly shown in Equation (10), the ultimate speed of the response is limited by the rate of change of the refractive index.

We may now summarize the performance in the following way. For a high  $Q$  cavity, the build-up of energy leading to the steady-state response is slow. The rate however at which energy exits the cavity is equally slow. This means once we input energy into the cavity and then change a cavity parameter (the index), satisfaction of the electromagnetic boundary conditions result in a shift in the resonant frequency.

#### Additional Considerations

Material dispersion, where the refractive index of the material used to construct the VCTF exhibits wavelength dependence, will influence the tuning characteristics of the filter and must be taken into account when designing the VCTF. Material dispersion is a well-understood phenomenon and can be accurately modeled in a variety of ways. Its effects can be compensated for in the specification of the chirped Bragg grating.

Finally the discussion and analysis above assumes that the cavity is lossless. This assumption is justified when the VCTF is constructed with low-loss components. If the losses become significant, the lossless assumption can still be justified by the insertion of an optical amplifier inside the cavity. The gain of the amplifier is set so as to overcome all losses encountered in the cavity.